Geometric and Physical Constraints on Recovering Snow Covered Area from SAR

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ABSTRACT

Snow covered area is an important variable in snowmelt runoff modelling. SAR can supply information on this parameter by detecting the decrease in the backscattering coefficient which occurs when the snowpack becomes wet. However, the method is subject to several geometric, geophysical and logistical constraints which limit its general applicability. These include missing coverage due to relief, reference image availability, inferring dry snow cover, validation and the sampling and time requirements for runoff modelling and forecasting. These are reviewed in this paper and where available, solutions are outlined along with their limits of applicability. Many of the topics discussed have relevance to other SAR applications.

INTRODUCTION

Wet snow cover can be detected using spaceborne C-band (wavelength 5.7 cm) synthetic aperture radar (SAR) such as ERS and Radarsat [1]. SAR derived estimates of wet snow covered area (SCA), and hence inferred estimates of dry and total SCA, are of interest to various applications including snowmelt runoff modelling [2]. As part of a broader project promoting the use of EO data in snowmelt hydrology, SAR wet snow mapping has been demonstrated over a variety of geographical regions including the Zillertal basin in the Austrian Alps, the Tjaktjajaure basin in northern Sweden and the Spey basin in the Scottish Highlands [3-8]. This work has revealed a number of geometric, geophysical and logistical constraints to general application of the method. These are each discussed below. However, the SAR wet snow mapping method is first briefly described.

SAR WET SNOW MAPPING

Theoretical Basis

At C-band, the penetration depth of dry snow is of the order of tens of metres and the backscatter mainly comes from the underlying surface [1,9]. In contrast, even 1 % liquid water by volume reduces the penetration depth to tens of centimetres. As most losses in the wet snow are due to absorption rather than volume scattering, the backscattering coefficient is substantially reduced [1]. Wet snow can therefore be detected by comparing calibrated backscatter values with those in a reference image from a period of no or dry snow cover.

Methodology

In order to ensure that the snow and reference images have the same imaging geometry, they are taken from the same repeat pass. Wet snow is detected by calibrating and registering both images, filtering each image to reduce speckle and then applying a threshold to their intensity ratio. Wet snow is detected if this is less than -3 dB. Relative calibration to radar brightness is sufficient for purposes of image ratioing [10] and registration of repeat pass images requires only translation. The ratioing cancels backscatter variations due to the local incidence angle. A transform for geocoding ratio images is defined by matching the reference image to a SAR image simulated from a DEM [11]; layover features are used as ground control points. A fuller description of the SAR wet snow detection method can be found in [1,4,6-8]

GEOMETRIC CONSTRAINTS

The primary constraint arising from the SAR image geometry is missing coverage. Specific constraints also apply to large basins.

Missing Coverage Induced by Relief

The geographic coverage provided by SAR is appreciably reduced by even moderate relief. Missing coverage arises where relief causes the local incidence angle (θ) to be particularly low or high. As a result wet snow detection is limited to local incidence angles between 17° and 78° [1]. This is due to foreshortening and specular effects at low angles, and the poor signal to noise ratio at grazing angles. Foreshortening and grazing are themselves limited by local incidence angle ($\theta \leq 0°$ and $\theta \geq 90°$ respectively). Beyond this additional problems of missing coverage arise due to layover and radar shadow [12].

Some control over the local incidence angles within a scene is available through the choice of imaging geometry, namely the look angle (the angle subtended at the antenna between the radar beam and nadir). At steep look angles layover and foreshortening are the primary sources of missing coverage. As the look angle increases, layover and foreshortening decrease while radar shadow and grazing increase. Amongst current spaceborne SAR systems, the mid-beam look angle (α) of ERS is fixed at 20° while Radarsat offers a mid-beam look angle of between 20° and 40°. For three basins of differing relief and mid-beam look angles of 20° and 40°, Table 1 lists the percentage area of each basin affected by missing coverage and the breakdown into layover, radar shadow, foreshortening and grazing (note: layover and foreshortening can overlap). DEMs of the basins were used to identify areas of layover and radar shadow [10] and to calculate local incidence angles [11]. All of these calculations were based on orbit parameters for actual ERS and Radarsat frames. The basins include a high relief alpine basin (the Zillertal in Austria, elevation range 560 to 3503 m), and two higher latitude basins of more moderate relief, the Tjaktjajaure basin in Northern Sweden (450 to 2044 m), and the Spey basin in Scotland (198 to 1284 m). The elevation ranges are listed to give a rough indication of the amount of relief.

Table 1. The effect of look angle α on the percentage area of missing coverage in three basins of differing relief, including the breakdown into layover, radar shadow, foreshortening and grazing [3,6,8].

Basin	α	Tot.	Lay.	Sha.	For.	Gra.
Zill.	20°	38.8	34.9	< 1	3.9	NA
Zill.	40°	10.6	0.9	0.4	9.3	NA
Tjak.	20°	12.0	6.0	0.08	8.0	0.01
Tjak.	40°	2.1	0.4	0.9	0.3	0.7
Spey	20°	21.8	7.4	0.06	18.6	0.003
Spey	40°	1.7	0.56	0.29	0.91	0.2

At the steeper, 20°, look angle (ERS or Radarsat), missing coverage affects a large part (38.8 %) of the Zillertal basin, most of which is layover. Missing coverage is considerably less (12 to 21.8 %) in the more moderate relief basins, but is still appreciable. Here, foreshortening rather than layover is the dominant cause. In all three basins radar shadow and grazing are comparatively insignificant.

Because the look angle varies across the image swath, the amount of missing coverage also depends on the range position of each basin within the swath. This effect can be observed in the results for the Tjaktjajaure and Spey basins. Based on the elevation range, the Tjaktjajaure basin would be expected to be worse affected than the Spey basin. However, the contrary is true due to the range positions the basins were imaged at, in these examples. Tjaktjajaure was imaged at far range, hence layover and foreshortening were reduced relative to mid-swath. The opposite occurs with the Spey which was imaged at near range. On adjacent passes to those used here, the basins will be imaged at a more/less distant range and hence will exhibit slightly less/more missing coverage.

At the shallower, 40°, look angle (Radarsat only) missing coverage is markedly lower in all three basins. This is due to the reduction in layover being much greater than the increase in radar shadow and grazing. While the Tjaktjajaure and Spey basins show a decrease in foreshortening the Zillertal basin shows an increase. This is due to part of the area that was previously affected by layover now being affected by foreshortening. Foreshortening is now the dominant source of missing cover in the Zillertal and Spey basins while radar shadow is the dominant source in the Tjaktjajaure basin. The differences between the Spey and Tjaktjajaure basins can once again be explained by their relative range positions.

The above examples illustrate that at steep look angles missing coverage can be a severe constraint to estimating wet SCA over regions of even moderate relief (1000 m variation in elevation). At shallower look angles, the problem is greatly reduced but can still exceed 10 % of the image in regions of high relief. Finally, it should be noted that steeper slopes, and hence missing coverage, more often occur at mid to higher elevations where snow cover is more likely [3].

Two approaches have been developed to reduce the effects of missing coverage:

- Image combination;
- Inferring wet snow cover in areas of missing coverage.

Image Combination

Missing coverage can be reduced appreciably by combining images taken from different viewing directions, such as the ascending and descending passes of a spaceborne SAR [1]. For example, the combination of ERS passes reduces missing coverage over the Spey and Zillertal basins to less than 1 % and 6 % respectively [3,6].

The usefulness of this approach is limited by the temporal lag between the ascending and descending passes which is latitude dependent. Wet snow detection requires both images to be taken close together in time during a period of little change in snow conditions. In the Alps (~47° N), where the wet snow detection method was originally developed, the lag between the two passes is only half a day [1]. However, at most other latitudes the lag is a day or more longer. For example, for the Spey and Tjaktjajaure basins the time lags are 1.5 and 6.5 days respectively. While snow conditions may remain stable over such intervals during a cold period of no snow melt, this is unlikely during melting periods. Hence, inferences on wet SCA based on image combination are unlikely to be valid in these basins.

Inferring Wet Snow Cover in Missing Coverage

A statistical method for inferring wet snow in areas of missing cover has been developed, based on zones of similar aspect and elevation [4,5]. It uses the following steps:

1. The image is classified into zones defined by elevation and aspect.

2. The area of wet snow, A_i, and other surfaces (excluding missing cover), B_i, is calculated for each zone i, and the proportion of wet snow cover for that zone is calculated as $P_i = A_i/(A_i+B_i)$.

3. If $P_i > T$ all areas of missing cover within that zone are classified as wet snow.

The use of a hard threshold causes wet SCA to be over/under-estimated within some zones. However, for an appropriate choice of threshold these errors will balance out in the total wet SCA. A value of T = 50 % has been used. This is suitable when the area of zones has a symmetric distribution with respect to P. Since this is not always the case a more optimal method is needed to select the threshold. An alternative would be to apply a fuzzy rather than a binary classification. Pixels in missing cover would be assigned their corresponding P_i value. Elsewhere, wet snow pixels would be assigned the value 1 and all other pixels the value 0. The total wet SCA could then be estimated by simply summing pixel values in the fuzzy classification.

The method needs at least part of any given aspect-elevation zone to be unaffected by missing cover and this determines how finely aspect and elevation are partitioned. In Tjaktjajaure, where the method has been applied over several melt seasons, 15° aspect zones and 100 m elevation zones were found to be adequate.

Spatial Coverage over Large Basins

The scan SAR and wide beam modes available with Radarsat enhance SAR capability for wide area coverage (> 100 km) by a single image. However, where two or more images are still required to cover a basin two constraints apply. The first is purely geometric while the second introduces a problem of geophysical interpretation.

- Where the basin just extends over consecutive frames in the azimuth direction the reference and snow frames need to be accurately mosaicked prior to ratioing. If mosaicking is left to after ratioing gaps can arise due to slight differences in the start and end times of repeat frames.

- Where it is not possible to cover the basin within the image swath, images from two or more distinct times will be needed to provide coverage. Hence, the problems of geophysical interpretation of snow maps from different dates, already noted earlier with respect to image combination, will apply. This problem can be circumvented by splitting the basin into smaller sub-basins each of which can be covered by a single swath.

GEOPHYSICAL CONSTRAINTS

The SAR snow mapping method is subject to a variety of geophysical constraints including reference image choice, other types of backscatter change, wet snow detection in forest, dry snow inferences and validation.

Choice of Reference Images

Images from cold winter periods with only dry or no snow cover give the best reference for detecting backscatter change due to wet snow. However, such conditions can be infrequent in temperate maritime basins having seasonal but generally wet snow cover, e.g. basins in the Scottish Highlands. Opportunities for acquiring suitable winter reference images will then be rare. In such cases reference images should be selected from long dry periods during the summer.

The dependence of reference images on specific surface conditions and speckle can be reduced by averaging multiple reference images, if available.

Other Types of Backscatter Change

Wet snow detection is based on backscatter change which can also arise from other causes, such as agricultural activity, flooding and wind roughening of open water. Land cover and elevation information can be used to mask out areas likely to be affected. However, mis-classification will occur where other change cannot be predicted.

Wet Snow Mapping in Forest

Mapping snow cover under forest is difficult with both SAR and optical sensors. It has been shown that wet snow can be detected by C-band SAR in sparse forests [13] but not in thicker forest [14]. Hence, land cover information should be used to mask out forested areas.

Inferring Dry Snow Cover

Following wet snow detection, dry snow cover must be inferred. If it is assumed that snow cover patterns remain similar from year to year, a map of dry snow cover can be built up from wet snow maps from later periods in previous melt seasons [7]. This requires an archive of SAR-derived wet snow maps from previous years. Where archive data is unavailable a "hill climbing" approach which classifies pixels lying above wet snow as dry snow, can be adopted [4,5].

The hill climbing approach assumes that snow cover is complete at higher elevations, but this is often not the case; for example, exposed ridges are often snow free. Hence, this approach tends to overestimate SCA. By contrast the archived data approach distinguishes between snow-covered and snow-free areas at higher elevations and is the preferred method if sufficient data is available.

Geophysical Validation

To check the accuracy of SAR derived (wet+dry) snow cover maps, they have been compared with snow cover maps derived from near coincident high resolution optical data.

In the Zillertal basin good agreement was found between snow maps derived from ERS and Landsat TM (7 day gap, 86.4 % agreement) and Radarsat and Landsat TM (2 day gap, 82.8 % agreement) [6-8]. In both cases SAR was observed to underestimate snow cover relative to TM.

By comparison, in the Tjaktjajaure basin marked differences were found between snow maps derived from ERS and Landsat TM (2 day gap) [4,15]. Overall the SAR SCA is 15 % less than the TM SCA but the differences are elevation dependent (Fig. 1).

- Above 1500 m, the SAR SCA is near 100 % and is considerably greater than the TM SCA. This is probably because of overestimation by the hill climbing approach used to infer dry snow cover, as noted above. The TM+SAR common SCA is also coincident with the TM SCA indicating all snow cover detected by TM is also detected by SAR.

- Between 1200 m and 1500 m, the TM SCA changes to being greater than the SAR SCA with the maximum SAR and TM SCA occurring at around 1400 m, although the SAR maximum is slightly greater and at a higher elevation than the TM maximum. Confusion between the SAR and TM SCA is indicated by the common SCA being less than either.

- Below 1200 m, SCA is significantly underestimated by SAR relative to TM and the common SCA is coincident with the SAR SCA indicating that all the snow cover detected by SAR is also detected by TM. Analysis of the TM image reveals that snow cover is increasingly patchy at these lower elevations. It is suspected that this patchiness reduces the backscatter change due to wet snow to below the -3 dB detection threshold. Such a reduction in backscatter change has been observed in areas of patchy wet snow elsewhere in Scandinavia [16] and in the Spey basin in the Scottish Highlands [3].

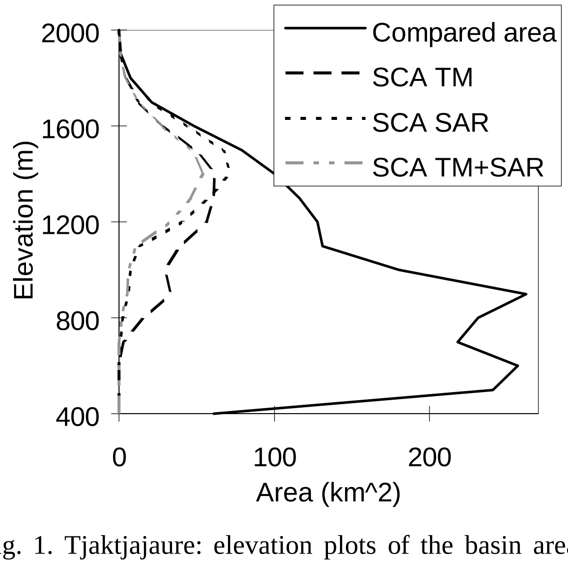

Fig. 1. Tjaktjajaure: elevation plots of the basin area, the SCA derived from Landsat TM (25/06/92) and ERS SAR (23/06/92) and the SCA common to both sensors.

If patchy snow cover is the cause of SAR underestimating SCA at lower elevations in higher latitude basins, similar effects might be expected in alpine basins. However, due to the greater relief in alpine basins, slopes are steeper and the transition zone from full to no snow cover is much narrower.

The SCA differences observed in the Tjaktjajaure basin need to be resolved before SAR derived SCA can be reliably used in snowmelt forecasting in similar basins, particularly if SCA estimates derived from SAR and optical EO are to be used together.

LOGISTICAL CONSTRAINTS

Snowmelt runoff modelling requires weekly estimates of SCA [17]. Also for near real-time forecasting of snowmelt runoff, SAR derived estimates of SCA must be available within a day of data acquisition. Below we discuss how these conditions can be met using current spaceborne SARs.

Temporal Coverage

Over most basins of interest four images can be acquired by ERS within its 35 day repeat cycle (i.e. using adjacent ascending and descending passes from the 16 day sub-cycle). This gives an average of one image every 8.25 days, just outside the one week requirement. However, the temporal pattern of coverage is latitude dependent due to the lag between ascending and descending passes, which was discussed earlier under image combination. In terms of even spacing of temporal coverage short lags are disadvantageous. For example, over Zillertal the interval between passes ranges from 0.5 to 18.5 days, while over Tjaktjajaure the interval between passes ranges from 6.5 to 12.5 days.

The shorter 24 day repeat cycle of Radarsat combined with a steerable beam means that basins of interest can be imaged more frequently than with ERS. The pattern of temporal coverage will still be determined by latitude. Radarsat and ERS temporal coverage will of course be reduced if other applications impose data acquisition conflicts.

Near Real Time Transfer of Data

During 1999, ERS data were used to derive snow cover maps for forecasting snowmelt runoff in Tjaktjajaure and Zillertal. While the required timescale was 24 hours, normal delivery of ERS PRI data takes two weeks. However, cooperation by ESA and D-PAF allowed a special fast data delivery chain to be formed. The raw SAR data was downloaded to the Neustrelitz receiving station and processed by DFD within 1.5 to 6.5 hours of data acquisition. Data transfer (130 Mbytes) to the customers in Austria and the UK then took between 5 and 20 minutes. Finally, geocoding and classification by the customer took under 2½ hours. This delivery chain permitted snow maps to be derived from descending (morning) passes within 6 hours. Ascending (evening) passes took longer due to data transfer not taking place until the following morning. However, snow maps were still derived well within 24 hours.

CONCLUSIONS

- While it has been clearly demonstrated that C-band SAR can be used to estimate snow covered area, general application of the method is constrained by the factors reviewed in this paper. Where available, possible solutions have been indicated.

- In regions of moderate to high relief geographic coverage can be constrained by missing coverage. This can be substantially reduced by using shallow incidence angles, such as are available from Radarsat (and will be available from Envisat). This approach is preferable to image combination, which is latitude dependent, and inferences based on aspect and elevation.

- Large basins introduce specific problems of image mosaicking and geophysical interpretation.

- SAR wet snow mapping is dependent on the availability of suitable reference images. These are more easily obtained under dry continental climates than wet maritime climates.

- The wet snow classification has to make allowance for other types of backscatter change and lack of snow detection in forest.

- For inferring dry snow cover from SAR images, use of an archived data approach is preferred to the hill climbing approach, again subject to suitable data availability.

- While snow maps derived from SAR and high resolution optical data show good agreement in an alpine basin, large elevation-dependent differences are observed in a higher latitude basin. At higher elevations the difference is due to incorrect inferences on dry snow cover. At lower elevations it is suspected that the difference is due to patchy snow cover being underestimated by SAR.

- Snowmelt runoff modelling requires weekly estimates of SCA. Of current spaceborne SARs Radarsat can meet this requirement while ERS can provide near weekly coverage, dependent on latitude.

- Data transfer and processing facilities are sufficiently fast for providing data for use in near real time forecasting of snowmelt runoff.

- While this paper is written in the context of snow mapping, many of the constraints equally apply to other SAR applications involving change detection and time series analysis. The problem of missing coverage needs to be addressed in any area of moderate to high relief. While the geophysical constraints are mainly application specific, the logistical constraints will be of concern to any applications requiring regular repeat coverage and near real-time data access.

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